Monitoring System for Suspended Sediment in Surface Water Using Remotely Sensed Data-ALOS/AVNIR-2

Asif M. Bhatti (CI-305)[1], Seigo Nasu (JAXA-PI -305)[2] and Masataka Takagi(CI)[3]

[1] Kochi University of Technology, Kochi, 782-8502, Japan.
[2, 3] Professor, Kochi University of Technology, Kochi, Japan.
Phone: 0887-57-2792, Email: asifmumtaz.bhatti@kochi-tech.ac.jp

ABSTRACT

The water quality and quantity "Q & Q" connection is vital for sustainable water resources development and management. Remote sensing makes it possible to monitor the water bodies effectively and efficiently and is most successfully used as part of a multidisciplinary approach to addressing natural resource questions. The heavy sediment load brought by feeding streams in most of the rivers and reservoirs is a major problem. The prime objective of the research project is to monitor suspended sediment concentrations (SSC) in surface waters of the Indus River by means of ALOS/AVNIR-2 data. Monitoring of suspended sediment concentrations using remotely sensed data have received the attention owing to strong relationship between suspended sediments and water surface reflectance. Reflectance of ALOS/AVNIR-2 band 3 and band 4 was used to develop the algorithms for estimation of suspended sediment concentrations. ALOS/AVNIR-2 data and optical modeling is coupled to cope with lack of ground truth data. The developed model and monitoring system is a useful practical tool for monitoring suspended sediments on seasonal bases and during floods. The research work demonstrates an example for the feasibility of ALOS/AVNIR-2 data for effective and efficient monitoring of suspended sediments in water bodies.

***Keywords*:** ALOS/AVNIR-2, Suspended sediments, Monitoring, Algorithm

1. INTRODUCTION

Sediment transport in a river basin strongly depends on stream flow conditions. The comprehensive understanding of the spatial and temporal patterns of the suspended sediment yield in the river basin is vital for effective water resources and environmental planning and management. The factors that determine sediment yields fall into four major categories [1]: i) climate; ii) geology; iii) relief; and iv) land use. Runoff water from watersheds provides most of the flow available to Pakistan's irrigation system. The Indus River faces threat from climate change because of its high dependency on glacier water. A substantial amount of sediment is usually picked up from the soil as these waters move to lower elevations under the force of gravity. While their sediments built the soils of the Indus Basin, they are now often a problem because they fill the reservoirs. Filling of reservoir with sediment reduce their water storage capacity and seal the bottoms of our recharge catchments so they are not able to pass their waters to the underlying aquifers quickly to prevent loss of a major portion of it by evaporation. High concentrations of suspended sediment in water are a critical element in the economic feasibility of a project and could shorten the useful life of many reservoirs & dams. The loss of storage capacity in reservoirs in the United States cost $ 100 million annually in dredging and related mitigation efforts [2]. The most often cited estimates of the global suspended sediment discharge to the ocean range between 15×10^9 $t\cdot yr^{-1}$ to 20×10^9 $t\cdot yr^{-1}$ where the best estimate may be about 20×10^9 $t\cdot yr^{-1}$ [3], of which over 25% is considered to be trapped by dam reservoirs [4].
The magnitude and frequency of sediment transport depend not only on the hydraulics of the river system, but also on the complex pattern of sediment availability from the sources in the basin [5] and associated extreme events. Identification of these sources and quantifying their effect is a major task for environmental technologist and water resources planners [6]. This necessitates a comprehensive study of sediment fluxes, the quantity of total sediment deposited in reservoirs, and the quantitative relation of sediment to the flow of water and impact of climatic change on sediment yield and river discharge. Arguments for the application of

remotely sensed data for water resources and environmental monitoring is compelling. The application of remote sensing in water resources research and management mainly consists of one of the three categories: mapping of watersheds and features, indirect hydrological parameter estimation and direct estimation of hydrological variables. Earth observation from space offers unique opportunities to obtain information regionally and globally. Remotely sensed data offer a unique perspective and are imperative for management and monitoring of earth resources from local to regional to global scale. The objective of present research work is to monitor suspended sediments in surface waters of the Indus River, Pakistan by means of ALOS/AVNIR-2 data.

2. STUDY AREA

The surface water resources of Pakistan mainly consist of flows of the Indus River and its tributaries. Archer, 2003 [7] characterized the upper Indus River by three contrasting hydrological regimes based on the mechanisms generating runoff during the summer season: i) melt of glaciers and permanent snow in high elevation drainage basins, where summer runoff is predominantly controlled by the temperature; ii) melt of seasonal snow, controlled by preceding winter and spring precipitation; and iii) winter and monsoon rainfall, controlled by precipitation in the current season.

The Indus River, Pakistan is one of the largest sediment producing rivers in the world. The total length of the Indus is about 2,900 km. The catchment area of the Indus River is 969000 km^2 with an annual runoff of 175 billion m^3 and annual sediment load of 470 million tons.

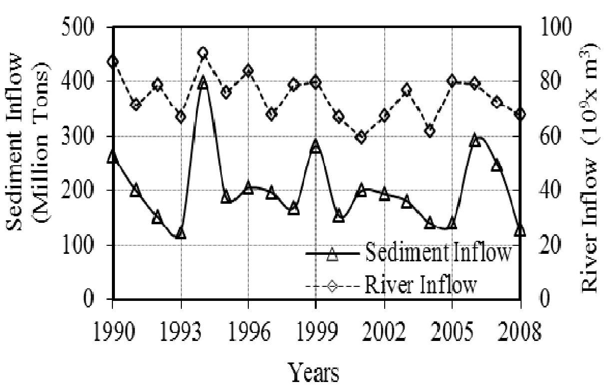

Figure 1. Annual sediment load computed from hydrograph survey [8]

The Tarbela Dam is the largest earth and rockfill dam of the world across the river Indus in Pakistan. The length of Tarbela dam reservoir is 97 km with an area of 260 km^2. Above Tarbela the catchment area is 169,650 km^2 with annual sediment load of 287 tons. Although the catchment area above Tarbela Dam accounts for only 17.5 percent of the total catchment area of the Indus, the annual sediment load above Tarbela accounts for 66 percent of the total sediment load of the river. The land area affected by soil erosion by water and wind is tabulated in table1. The distribution and composition of sediments in relation to the magnitude of the flow and along the Indus River is not really known resulting in various socio-economic and environmental problems. The impact of climatic change and extreme events has also diverse impact on soil erosion and sediment movements in the study area. The availability of long term in situ data is inevitably a key constraint for accurate assessment of sediment load in the water bodies. There is dire need to adopt methodology for effective and efficient monitoring of suspended sediments along the river.

Table 1. Land area affected by soil erosion by water and wind in South Asia [9]

Country	Water Erosion (Mha)	Wind Erosion (Mha)	Total land Area (Mha)
India	32.8	10.8	328.8
Iran	26.4	35.4	165.3
Pakistan	7.2	10.7	79.6
Afghanistan	11.2	2.1	65.3
Nepal	1.6	0	14.7
Bangladesh	1.5	0	14.4
Sri Lanka	1.0	0	6.6
Bhutan	0.04	0	4.7
Total	81.74	59.0	679.4

3. METHODOLOGY

3.1. Laboratory Analysis

Experiments were performed in the laboratory to elucidate the effect of different concentration of suspended sediments on reflectance signals. The spectral signatures of varying concentration of suspended sediments were investigated in detail. The experiment was performed in the laboratory under controlled conditions and the depth of water column was kept constant at 40 cm. The spectral reflectance of water with varying concentration of suspended sediments (0 to 1000 mg/l) was collected by means of a hyperspectral Field SpecPro FR Spectroradiometer (Analytical Devices, Inc., Boulder, CO).

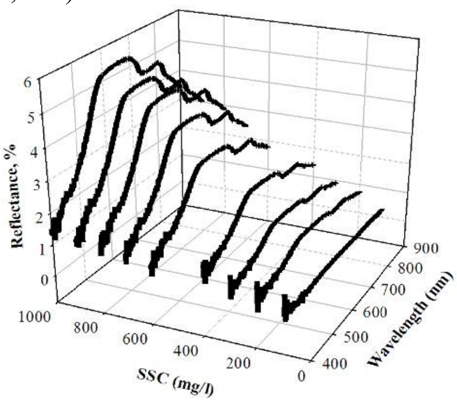

Figure 2. Spectral reflectance of water with varying concentration of collected soil samples

It was observed that the reflectance increase with the increase in suspended sediments concentration and the peak reflectance shifts towards longer wavelength. The systematic trend in reflectance pattern was observed through the entire range of spectrum. To investigate the field application of collected hyperspectral reflectance, the collected spectra were integrated to ALOS/AVNIR-2 band widths.

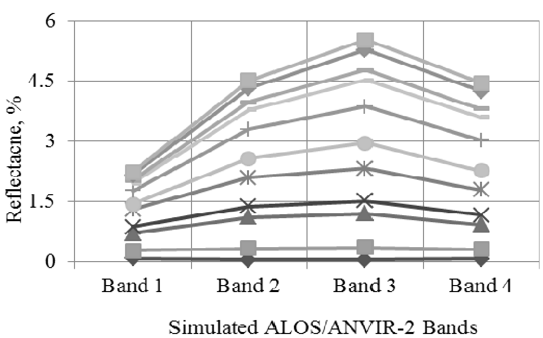

Figure 3. Simulated ALOS/AVNIR-2 reflectance of varying SSC (0-1000 mg/l)

The regression model was developed between the simulated ALOS/AVNIR-2 data and SSC. A good correlation exists between the simulated data and suspended sediment concentration (SSC). ALOS / AVNIR-2 band 3 and band 4 were found to be well correlated with SSC. The developed reflectance model $(B_4+B_3)/(B_3/B_4)$ derived from series of laboratory experiments is the best predictor of SSC. The subscripts 4 and 3 represent band 4 and band 3 of ALOS optical sensor AVNIR-2.

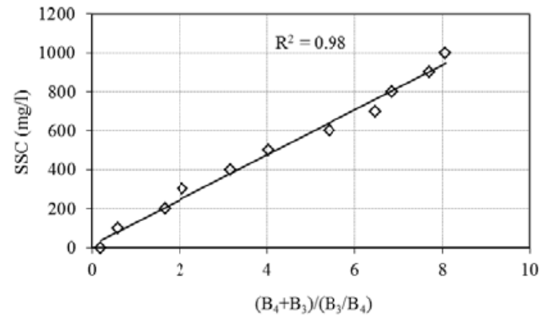

Figure 4. Relationship between SSC and developed reflectance model

3.2. ALOS Data processing and Analysis

The Advanced Land Observing Satellite (ALOS) was launched on 26 January, 2010. The ALOS has two optical sensors called PRISM and AVNIR-2, and an L-band Synthetic Aperture Radar called PALSAR. The wavelengths covered by the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) include: Band 1 (0.42-0.50 µm), Band 2 (0.52-0.60 µm), Band 3 (0.61-0.69 µm) and Band 4 (0.76-0.89 µm). The ALOS/AVNIR-2 images acquired during 2006, 2009 and 2010 were selected for the purpose of this research study. These images encompass the Indus River, Tarbela Dam and surrounding area in the Pakistan. The suspended sediment concentration data of the Indus River at the monitoring station on the day of satellite overpass was obtained from Water and Power Development Authority (WAPDA), Pakistan.

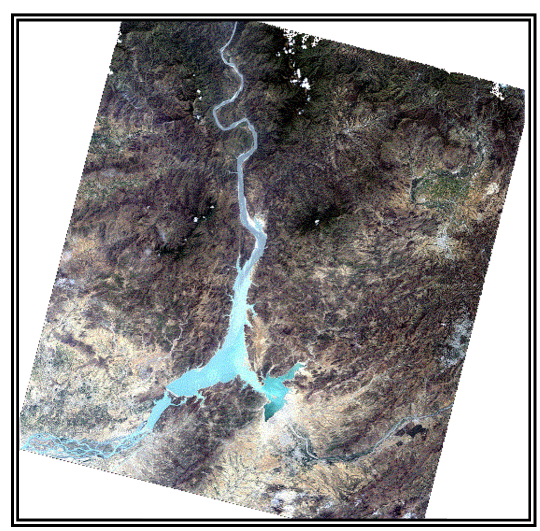

Figure 5. ALOS/AVNIR-2 image of Tarbela Dam & Indus River, Pakistan. *Acquisition date: July 14, 2009*

For each band the image digital numbers (DN) were converted to top of atmosphere (TOA) spectral radiance (L) by using the following equation;

$$L = DN * a + b$$

Where L is radiance ($Wm^{-2}Sr^{-1}\mu m^{-1}$), “a” is gain and “b” is offset. The value of a and b can be retrieved from the scene header file. The TOA spectral radiance is converted into TOA reflectance for each band by using the following equation [10].

$$R(i) = \frac{\pi L(i)}{\mu_s E_s(i)}$$

Where i = 1,2,3 and 4; $\mu_s = \cos(\theta)$, θ is the solar zenith angle, E_s ($Wm^{-2}\mu m$) is the solar TOA irradiance. The solar spectral irradiance values are not provides with the product. It can be computed using article from Thuillier, 2003 [11] and are as follow.

Table 2. Spectral Solar irradiance [12]

Band	Band 1	Band 2	Band 3	Band 4
Central wavelength (nm)	460	560	650	820
Solar spectral irradiance $Wm^{-2}\mu m^{-1}$	1943.3	1813.7	1562.3	1076.5

The TOA measurements are then corrected for atmospheric effects. The atmospheric correction is the process of retrieving the surface radiance and surface reflectance from the satellite radiances. The dark pixel subtraction technique was used to remove or reduces the atmospheric influence on water-leaving light signals. A darkest pixel subtraction approach is simple and feasible and may apply when no ground truth data corresponding with the image is available. Hadjimitsis et al. [13] reported that, from an operational point of view, the darkest pixel approach was preferred over more sophisticated techniques that require atmospheric and meteorological data. The dark pixel subtraction is based on the assumption that an effective black body exists in the image, resulting in a pixel value of zero [14]. The minimum pixel value for that point in each band is because of atmosphere and subtracted from the corresponding band. In the upstream area of the Indus River small isolated clean water pond located in the mountains with the minimum pixel values was considered for the purpose of atmospheric correction.

It was observed that the reflectance value along the river reach vary from point to point and strongly depends on the amount of suspended sediment concentration. However, it was seen that the reflectance value near the dam body and 30 km upstream shows a quite different behavior with more value in the NIR domain. The rational is because the water velocity becomes slow in the reservoir near the dam body and the floating material may cause the different response of spectral signature acquired by the sensor. The reflectance along the river reach is illustrated in the figure 6. The field application of remotely sensed data demands for ancillary field data. However, the problem in the research study area is that the suspended sediment concentration at only one sampling point 67 km upstream of the dam is known. There is no other data available for the research area. To deal with lack of in situ data, remotely sensed data is coupled with optical modeling and the desired parameter is derived by model inversion techniques. The temporal and spatial resolution of visible satellite imagery (some to several days) and the climatic constraints (cloud coverage) is constraint to observe the periodic distribution of suspended sediment in water bodies.

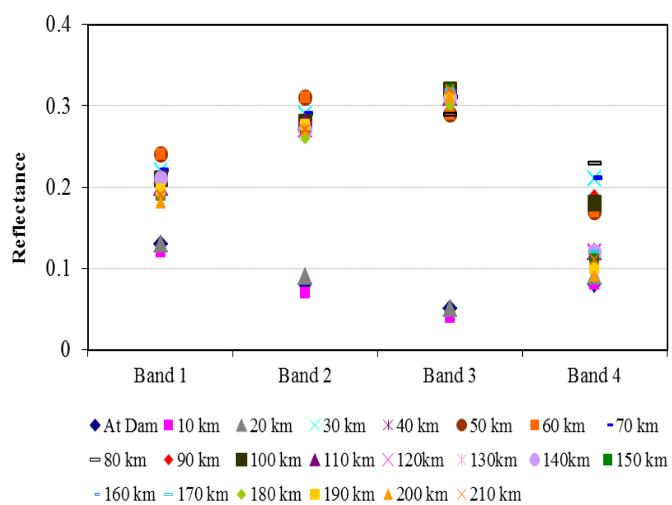

Figure 6. Reflectance value along the Indus River

4. MODELLED SPECTRAL REFLECTANCE

The relationship between reflectance R, inherent optical properties (IOPs) of the medium, absorption coefficient $a(\lambda)$ and backscattering coefficient $b_b(\lambda)$ is expressed as Morel [15];

$$Rrs(\lambda) = \frac{f}{Q} \frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$$

Where f is a coefficient and the commonly adopted value of f is 0.33, which is valid for zenith sun and for large variety of natural waters. The value of factor Q (ratio of upwelling irradiance to upwelling radiance) is ~ 3.4 [16]. For many studies, Q is often arbitrarily chosen as a spectral constant. However, Carder et al., [17] found that Q is not spectrally constant for the 1990 stations, and there was a trend for Q to increase with wavelength (an inverse trend compared with b_{bs}).

The value of 3.14 is used for analysis. In the research study area during the flood season (June-October), the suspended matters in the water are mainly composed of sediments. The presence of chlorophyll in the water is neglected. So, the absorption and scattering by chlorophyll is not taken in to account. The absorption coefficient $a(\lambda)$ and backscattering coefficient $b_b(\lambda)$ is written as follow;

$$a(\lambda) = a_w(\lambda) + a_y(\lambda) + a_s(\lambda)$$
$$b_b(\lambda) = b_{bw}(\lambda) + b_{bs}(\lambda)$$

Where the subscript w, y, and s represents water, colored dissolved organic mater (CDOM), and total suspended sediments (TSS).

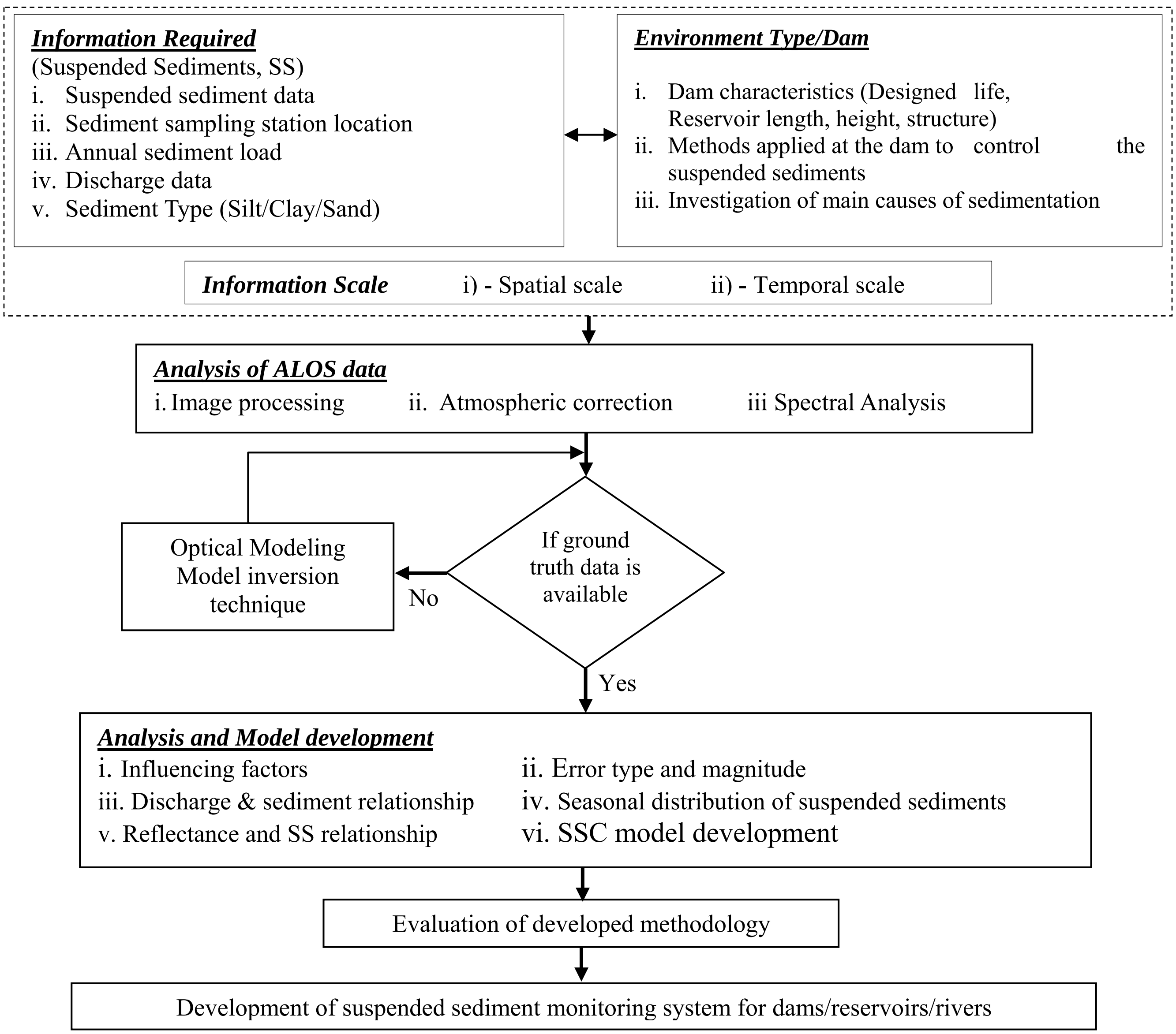

Figure 7. Frame work for development of suspended sediment estimation model

The value of a_w and b_{bw} are taken from Smith and Baker [18] for the range 400-800 nm. a_y is modeled as follow;

$$a_y(\lambda) = a_y(\lambda_o)e^{-k(\lambda-\lambda_o)}$$

λ_o = 400 nm, $a_y(\lambda_o)$ =0.3 m^{-1} and S=0.014 m^{-1}. Absorption by sediment is modeled as [19].

$$a_s(\lambda) = k_1 C_s^{k_2} (\lambda_0/\lambda)$$

k_1 = 0.05, k_2 = 1.1 & λ_o= 400 nm and C_s is suspended sediment concentration (mg/l). Light scattered by suspended sediment is modeled using the Mie theory. $b_{bs}(\lambda)$ is written as [20];

$$b_{bs} = \frac{3C}{2\rho} \cdot \frac{1}{\ln(D_2/D_1)} \int_{D1}^{D2} Q_{bb} . D^{-2} dD$$

C is suspended sediment concentration, ρ is the sediment density = 2600 kg/m³. Q_{bb} is the backscattering efficiency factor of the suspended particle of refractive index m_r, The refractive index of sediment is taken as 1.125. D_2 and D_1 represents maximum and minimum diameter of the suspended particles (200 - 0.01 µm), which include variety of suspended particles.

5. RESULT & DISCUSSION

The developed modeled reflectance is simulated to ALOS/AVNIR-2 band widths: Band 1 (0.42-0.50 µm), Band 2 (0.52-0.60 µm), Band 3 (0.61-0.69 µm) and Band 4 (0.76-0.89 µm) for comparison purpose with AVNIR-2 data and computational purpose for SSC estimation. The developed modeled spectra are simulated in to ALOS band width as illustrated in figure 8.

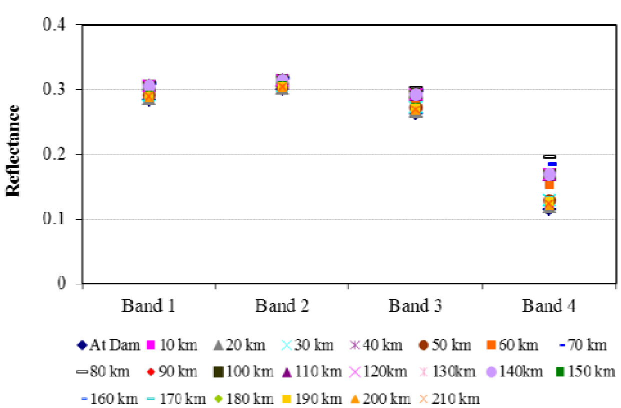

Figure 8. Simulated modeled reflectance spectra in AVNIR-2 band widths along the river

Mobley [21] have mentioned different values for colour dissolved organic matters in coastal and estuarine waters. The average value of 0.3 m^{-1} for the river is assumed and kept constant for the along the river. With the SSC of 250 mg/l the modeled spectra was developed and simulated into AVNIR-2 band widths. The simulated modeled reflectance data and AVNIR-2 reflectance data at the same sampling point was compared as shown in figure 8. It was observed that the difference between the two values was minimal in the green, red and NIR domain and overall showed well agreement. However, in the Band 1 (blue domain) the difference was observed. The rational is that the chlorophyll concentration is unknown and chlorophyll has influence in the blue region.

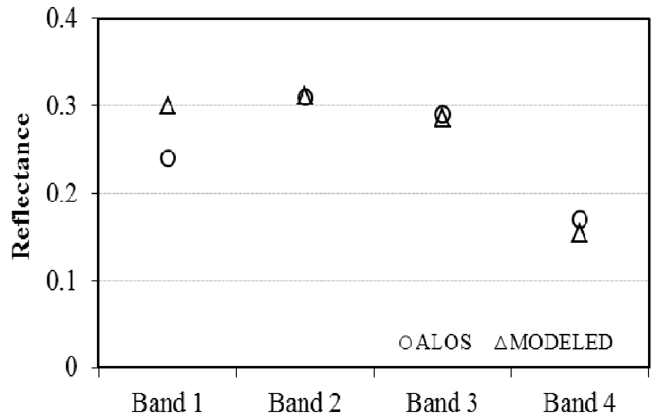

Figure 9. Comparison between modeled and ALOS/AVNIR reflectance data

By considering the absorption and scattering by chlorophyll, the difference in the Band 1 values may minimized. It proves that the proposed approach is applicable for estimation of suspended sediments in turbid water bodies and amount of suspended sediments can be estimated. The input suspended sediment concentration at other points are assumed or estimated by lab based model and a modeled reflectance spectrum was generated. The developed spectrums were simulated to the same band widths of AVNIR-2 sensors. The procedure consists in minimizing the difference between AVNIR-2 data and modeled reflectance data, by varying the value of input suspended sediment concentration. The output value with minimum difference in the red and NIR domain is the suspended sediment concentration at the point and the resultant spectra represents the spectral shape and magnitude at that corresponding point. By adopting the same approach, the suspended sediment concentration along the river at every 10 km was retrieved. For the purpose of computation and simulation of data the spread sheet was developed in the Microsoft Office Excel. It is worth to mention that the proposed technique is only applicable to turbid water when the image reflectance represents the water bodies. If any floating material is present on the water body, the proposed methodology will not provide accurate results. In such cases, by minimizing the difference in the NIR domain will lead to estimate the SSC in the water body.

The developed remote sensing methodology enables retrospective analysis of the AVNIR-2 sensor data of Indus River, Pakistan. By adopting the proposed methodology, the satellites archives may become a valuable resource for water resources engineers and researchers to remotely monitor the water bodies in the absence of ground truth data. The proposed methodology is considered not to be susceptible to the lack of ground truth data and weather conditions. Based on the proposed method, the satellite sensor data can become an independent measurement tool and the lack of sophisticated concurrent ground truth observations will not hamper the monitoring and modeling the water bodies.

5.1 SSC along the River Reach

The in situ suspended sediment concentration at the monitoring station 67 km upstream of the dam was 255 mg/l (sand 20%, silt 55% and clay 15%) on October 6, 2006. The simulated model bands were compared with ALOS spectral signals of the same sampling station. By adopting the same approach, the suspended sediment concentration along the river at every 10 km was retrieved as depicted in figure 10.

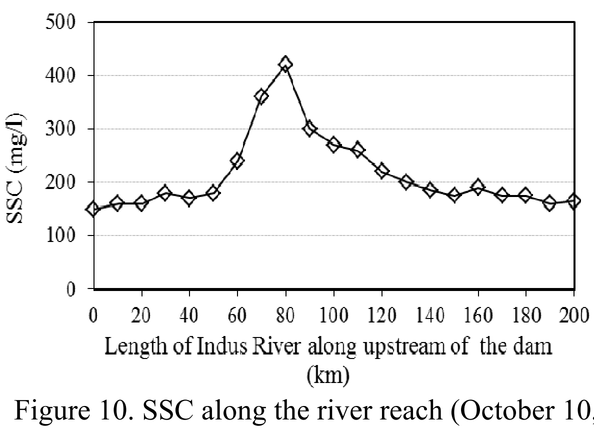

Figure 10. SSC along the river reach (October 10, 2006)

It is evident from the graphical presentation that the SSC vary along the river and the peak was observed at about 70 km upstream of the dam. In the range from 60km to 90km upstream of the dam, the amount of suspended sediments is significant and tends to decrease towards dam body. The velocity of the river inflow containing sediments decreases upon entering Tarbela reservoir, which reduces the sediment carrying capacity of the river water. The coarse sediment tends to deposit in the upper reaches of the reservoir, while the finer particles travel downstream towards the dam.

The graphical demonstration of suspended sediment distribution reveals that heavy sediment load is settling upstream of the dam in the range from 60 km to 90 km, thus reducing the storage capacity of the dam. The periodic examination of the sediment deposits and distribution in the upstream and downstream of the dam is vital to enhance the mitigation efforts for reduction of sediments. The contribution of sediment load is significant from the upstream catchment area. The adopted methodology proved to be useful for quantification of SSC along the river reach. Integrated water resources management in an organized and coordinated manner is the solution to deal with management activities in the upstream area.

5.2 SSC Model Development

The ALOS/ AVNIR-2 bands 3 and 4 were selected to develop the relationship between reflectance and suspended sediment concentration because SSC is strongly correlated with red and NIR domain. The developed ALOS/AVNIR-2 reflectance model (2 band Model) $(B\lambda_4+B\lambda_3)/\ (B\lambda_3/B\lambda_4)$ derived from series of experiments is considered to be the best predictor of SSC in the research study area. The subscripts 4 and 3 represent band 4 and band 3 of ALOS optical sensor AVNIR-2. The term $(B\lambda_4+B\lambda_3)$ represents the spectrum features of low and high concentrations of the suspended sediments and provides solution for the estimation of different sizes of sediments within the water body. However, the influence of chlorophyll-a concentration on red domain (Band 3) is well documented in literature. The term of $(B\lambda_3/B\lambda_4)$ reduce the chlorophyll interference to the low suspended sediment concentration.

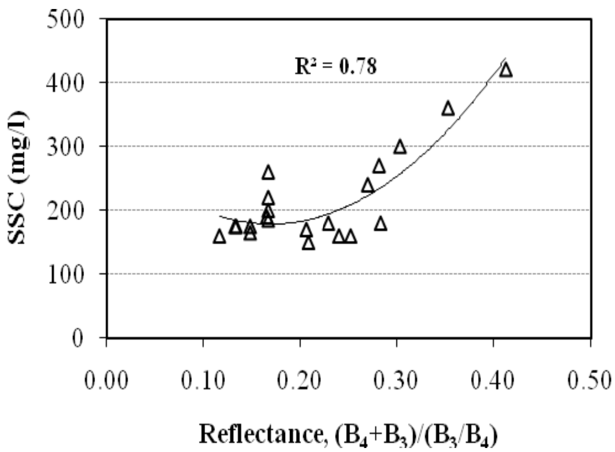

Figure 11. Relationship b/w SSC (mg/l) and reflectance model

Regression model was developed in order to quantify the suspended sediment along the Indus River. The correlation coefficient of 0.78 was obtained by applying the combination of two band model approach as graphed in the figure 11. It is concluded that the ratio of AVNIR-2 Band 3 and Band 4 by applying 2 band model approach is the best predictor of SSC. The developed model for estimation of suspended sediment concentration (SSC) is of the following form;

$$SSC(mg/l) = m[(B_4 + B_3)/(B_3/B_4)]^2 - n[(B_4 + B_3)/(B_3/B_4)] + l$$

where *m, n* and *l* are empirical coefficients.

6. CONCLUSION

Remote sensing has many actual and potential applications for water resources and environmental monitoring and management. The spatial and spectral resolution of ALOS/AVNIR-2 sensor makes it feasible for water quality monitoring and management. The ALOS/AVNIR-2 band 4 and band 3 (2 Band Model) is found to be the best predictor of suspended sediment concentration. In the present research work the concerned water quality parameter was suspended sediment. However, ALOS/AVNIR-2 is also useful for chl-a, color dissolved organic matter (CDOM) and total suspended sediment (TSS). The ANVIR-2 band 4 (0.76-0.89 µm) is found to be closely correlated with suspended sediment concentration in water bodies. The inversion technique is feasible to cope with lack of ground truth data problem. The integration of satellite data, in situ data, and optical model is an effective and efficient tool for monitoring erosion, deposition areas and sediment distribution in water bodies. If the concentration of one water quality parameter is known, the concentration of other parameters on the same sampling point may estimate by model inversion technique. The proposed methodology is effective and efficient to deal with sediment management in large rivers. In developing countries the ground truth data is often minimal or unavailable. It is difficult for resource managers to plan strategy to cope with sedimentation and erosion problems. The usefulness of the research is to make possible to work with minimum data with high reliability and efficiently. The research has shown the feasibility of multispectral data to estimate the suspended sediments in the surface water of rivers and reservoirs.

7. FUTURE OUTLOOK

The present paper describes the modelling and monitoring of suspended sediment in the Indus River, Pakistan. However, under the same project the ALOS/AVNIR-2 data is also being used to elucidate the impact of climate change on land use change and erosion in the Yoshino River basin, Shikoku, Japan. The outcomes of the research will be useful for the researchers and will be published later.

ACKNOWLEDGEMENT

This research is conducted under Japan Aerospace Exploration Agency (JAXA) RA-2 ALOS project. The authors (JAXA PI-305) wish to acknowledge the logistic support provided by JAXA, Japan.

REFERENCES

[1] Meade, R.H., Yuzyk, T.R., Day, T.J., 1990, “Movement and storage of sediment in rivers of the United States and Canada”, In: Wolman, M.G., Riggs, H.C. (Eds.), *Surface Water Hydrology*, Geological Society of America, Boulder, pp. 255-280.

[2] Julien, R.Y., 1995, “*Erosion and sedimentation*”, Cambridge University Press, New York, pp. 279.

[3] Walling D. E, 2009. *The Impact of global change on erosion and sediment transport by rivers: current progress and future challenges*. The United Nations World Water Assessment Programme, UNESCO-IHP Scientific Paper, UNESCO.

[4] Vorosmarty, C. J., Meybeck, M., Fekete, B. and Sharma, K., 1997, "The potential impact of neo-Cartorization on sediment transport by the global network of rivers", *In: Proceedings of the Rabat Symposium*, IAHS Publication No. 245,261.

[5] Ali, K.F. and De Boer, D.H., 2007, "Spatial patterns and variation of suspended sediment yield in the upper Indus River basin, northern Pakistan", *Journal of Hydrology*, 334, 368-387.

[6] Bhargava, D. S., and Mariam, D. W., 1991, "Effects of suspended particle size and concentration on reflectance measurement", *Photogrammetric and Engineering Remote Sensing*, 57, 519–529.

[7] Archer, D., 2003, "Contrasting hydrological regimes in the upper Indus basin", *Journal of Hydrology*, 274, 198-210.

[8] Water and Power Development Authority (*WAPDA*), 1991, "*Tarbela second periodic inspection*", Pakistan, Volume: 2, Sec: 20.5 (b), page 20-12.

[9] Lal R., 2001, "Soil degradation by erosion", Land Degradation and Development, 12: 519 –539.

[10] Vermote, E., et al., 1997, "Second simulation of the satellite signal in the solar spectrum: an overview", IEEE Transactions on Geoscience and Remote Sensing, 35 (3), 675-686.

[11] Thuillier, G., 2003, "The solar spectral irradiance from 200 to 2400 nm as measured by the solspec spectrometer from the Atlas and Eureca missions", Solar P*hysics,* 214: 1–22, Kluwer academic Publishers, Netherlands.

[12] ESA, "Information on ALOS AVNIR-2/PRISM products for ADEN user", European Space Agency.

[13] Hadjimitsis, D.G., et al., 2004, "An assessment of the effectiveness of atmospheric correction algorithms through remote sensing of some reservoirs", *International Journal of Remote Sensing*, 20, pp. 3651–3674.

[14] Tyler, A. N., et al., 2006, "Remote sensing of the water quality of shallow lakes: A mixture modeling approach to quantifying phytoplankton in water characterized by high-suspended sediment", *International Journal of Remote Sensing*, Vol. 27, No. 8, 1521–1537.

[15] Morel, A. and Louis Prieur, 1977, "Analysis of variation in ocean color", *Limnology and Oceanography*, Volume 22, Issue 4, 709-722.

[16] Gordon, H. R., Brown, O. B., and Jacobs, M. M., 1975, "Computed relationships between the inherent and apparent optical properties of a flat homogeneous ocean", *Applied Optics*, 14, 417–427.

[17] Carder K. L., 1991, "Reflectance model for quantifying chlorophyll a in the presence of productivity degradation products", *J. Geophys. Res.,* 96, 20,599-20,611 (1991).

[18] Smith, R. C., and Baker, K., "Optical properties of the clearest natural waters", *Applied Optics*, 20(2):177–184, 1981.

[19] Buiteveld, H., 1995, "A model for calculation of diffuse light attenuation (PAR) and Secchi depth", *Neth. J. Aquat. Ecol.,* 29:55–65.

[20] Forget, P., et al., 1999, "Inversion of reflectance spectra of non-chlorophyllous turbid coastal waters", *Remote Sensing of Environment,* 68:264–272.

[21] Mobley, C.D., 1994, "*Light and Water: Radiative Transfer in Natural Waters"*, Academic Press, San Diego.